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Environmental Effects

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A Review of Transfer Factors for Assessing the Dose from Radionuclides in Agricultural Products

By Y. C. Ng*

Abstract: *The dose to man from radionuclides released to the environment is generally assessed with mathematical models that require transfer factors as input parameters to predict the concentration of radionuclides in foodstuffs. This article summarizes recent attempts to review the worldwide literature and derive updated transfer factors to predict concentrations of radionuclides in terrestrial foods using equilibrium models. Updated transfer coefficients to predict the concentration of a radionuclide in cow's milk and other animal products from that in feed are presented as well as concentration factors to predict the concentration of a nuclide in a food or feed crop from that in soil. Comparing the updated transfer coefficients with those in existing tables leads to suggested changes in the transfer coefficients for milk and beef. Soil-to-plant concentration factors are extremely variable, which limits the usefulness of a single concentration factor to predict the uptake of a radionuclide into crops from soil. The potentially large uncertainty associated with predicting the uptake of radionuclides by plants from soil at a particular location may be reduced by considering the dominant crops and soil types in the area and how various soil properties affect the concentration factor. The updated transfer factors may be useful in assessing transport through terrestrial food chains when site-specific information is not available. In addition, they provide a basis for systematically updating existing tables of transfer factors for generic assessments.*

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Ingestion of contaminated terrestrial foods is one potentially important mode of exposure that must be considered when assessing the dose to man from radionuclides released to the environment. Transport of radionuclides through terrestrial food chains is usually evaluated with models designed for chronic-exposure situations where the concentrations of radionuclides in food products and environmental media are assumed to be in equilibrium.[1,2] The Nuclear Regulatory Commission (NRC) provides this kind of model in Regulatory Guide 1.109 (Refs. 3 and 4) to evaluate the dose from ingestion of terrestrial foods contaminated by radionuclides routinely released to the atmosphere and hydrosphere from light-water reactors. The Regulatory Guide 1.109 models evolved from similar models in the HERMES computer code.[5]

These models require nuclide- or element-specific transfer factors for predicting concentrations in terrestrial foods from those in vegetation or soil. Elemental transfer factors needed in Regulatory Guide 1.109 models include the following:

B_v, the soil-to-plant concentration factor, the ratio of the concentration of an element in fresh vegetation to that in dry soil

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Table 1 Transfer Factors from U. S. Nuclear Regulatory Commission Regulatory Guide 1.109*

Element	B_{iv} veg/soil	F_m(cow) milk, d/L	F_f meat, d/kg
H†	4.8 E+00	1.0 E−02†	1.2 E−02
C†	5.5 E+00	1.2 E−02	3.1 E−02
Na	5.2 E−02	4.0 E−02‡	3.0 E−02
P	1.1 E+00	2.5 E−02	4.6 E−02
Cr	2.5 E−04	2.2 E−03	2.4 E−03
Mn	2.9 E−02	2.5 E−04	8.0 E−04
Fe	6.6 E−04	1.2 E−03	4.0 E−02
Co	9.4 E−03	1.0 E−03	1.3 E−02
Ni	1.9 E−02	6.7 E−03	5.3 E−02
Cu	1.2 E−01	1.4 E−02	8.0 E−03
Zn	4.0 E−01	3.9 E−02	3.0 E−02
Rb	1.3 E−01	3.0 E−02	3.1 E−02
Sr	1.7 E−02	8.0 E−04‡	6.0 E−04
Y	2.6 E−03	1.0 E−05	4.6 E−03
Zr	1.7 E−04	5.0 E−06	3.4 E−02
Nb	9.4 E−03	2.5 E−03	2.8 E−01
Mo	1.2 E−01	7.5 E−03	8.0 E−03
Tc	2.5 E−01	2.5 E−02	4.0 E−01
Ru	5.0 E−02	1.0 E−06	4.0 E−01
Rh	1.3 E+01	1.0 E−02	1.5 E−03
Ag	1.5 E−01	5.0 E−02	1.7 E−02
Te	1.3 E+00	1.0 E−03	7.7 E−02
I	2.0 E−02	6.0 E−03	2.9 E−03
Cs	1.0 E−02	1.2 E−02‡	4.0 E−03
Ba	5.0 E−03	4.0 E−04‡	3.2 E−03
La	2.5 E−03	5.0 E−06	2.0 E−04
Ce	2.5 E−03	6.0 E−04‡	1.2 E−03
Pr	2.5 E−03	5.0 E−06	4.7 E−03
Nd	2.4 E−03	5.0 E−06	3.3 E−03
W	1.8 E−02	5.0 E−04	1.3 E−03
Np	2.5 E−03	5.0 E−06	2.0 E−04§

*Table 1 is a copy of Table E−1, "Stable Element Transfer Data," in Regulatory Guide 1.109, Rev. 1 (Ref. 4). Unless otherwise indicated, data in this table are from Y. C. Ng et al., *Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices, IV. Handbook for Estimating the Maximum Internal Dose from Radionuclides Released to the Biosphere*, USAEC Report UCRL-50163-Pt 4, Lawrence Radiation Laboratory, NTIS, May 1968.

†Meat and milk coefficients are based on specific activity considerations.

‡Data from R. J. Garner, *Transfer of Radioactive Materials from the Terrestrial Environment to Animals and Man*, CRC Press, Cleveland, Ohio, 1972.

§Data from R. S. Booth et al., A Systems Analysis Methodology for Predicting Dose to Man from a Radioactivity Contaminated Terrestrial Environment, in *Radionuclides in Ecosystems*, Proceedings of the Third National Symposium on Radioecology, Oak Ridge, Tenn., May 10–12, 1971, D. J. Nelson (Ed.), USAEC Report CONF-710501-P2, pp. 877-893, Oak Ridge National Laboratory, NTIS, 1971.

F_m, the transfer coefficient to cow's milk, the fraction of the element ingested daily by a cow that is secreted in 1 L of milk

F_f, the transfer coefficient to meat, the fraction of the element ingested daily by an herbivore that can be measured in 1 kg of muscle from the animal

These three transfer factors are calculated at steady-state or equilibrium conditions; F_f can also be calculated at slaughter.

The transfer data of Table 1, which is taken from Regulatory Guide 1.109 (Ref. 4), are presented as generic parameters to be used in evaluating compliance with Appendix I of Title 10, *Code of Federal Regulations*, Part 50, when site-specific data are lacking. Additional generic values are presented for the transfer coefficient of several elements to goat's milk. Transfer coefficients have also been derived to predict the transfer of radionuclides from feed to other animal products including pork, lamb, chicken, and hens' eggs.[5,6]

This article presents recent estimates of elemental transfer factors for terrestrial foods for a large number of radionuclides associated with the nuclear fuel cycle. The review focuses mainly on experimentally based estimates of B_v, F_m, and F_f. Updated transfer coefficients of selected elements are presented for other animal products. The review is based primarily on the author's recent publications and presentations[7–10] and is intended to be general rather than comprehensive. The literature relevant to the transfer factors for all the potentially significant radionuclides is too vast to summarize in a single review article.[11] Indeed, it has been appropriate to devote an entire article to the transfer factors of one or two elements.[12]

In the absence of site-specific data, the updated values may be used as input parameters in Regulatory Guide 1.109 models and similar models for predicting concentrations in foods under equilibrium conditions. Comparing the updated transfer factors with those in existing tables leads to suggested changes in the current values.

This article is not intended to present complete updated tables or recommend values of transfer factors. Systematically updating tables of transfer factors would require numerous assumptions and consideration of much additional information and therefore lies outside the scope of this review. Recommending parameter values would require criteria specifying the desired level of conservatism in the predicted concentrations, i.e., the desired balance between overprediction and underprediction. Such criteria would be expected to vary with the specific objectives of individual assessments.

The reader should recognize that transfer factors derived from the literature are subject to numerous shortcomings. Considerable judgment must be exercised by the investigator in evaluating the available data. For reasons of opportunity or convenience, parameter values are often based on experiments that were designed for purposes other than the evaluation of transfer factors. These estimates may depart from the strict definition of the parameter. For example, a factor based on a particular set of short-term observations may differ markedly from the steady-state or equilibrium value obtained over the long term. Furthermore, a transfer factor that is weighted toward a particular site may yield highly misleading predictions when applied to a different site. These considerations enhance the inherent natural variability of transfer factors.

The F_m is discussed first because it is the best-documented transfer factor. The F_f is discussed next. The data base for F_f is more limited, and well-characterized F_f values are few and largely undocumented. The B_v is discussed last. The data base for B_v is voluminous, but B_v values vary over such a broad range (depending on plant characteristics, soil properties, and other factors) that predictions of radionuclide uptake from soil by plants are associated with a large uncertainty. As an aid in the discussion of transfer factors, an explanation of the derivation of the F_m, F_f, and B_v values in Regulatory Guide 1.109 (Table 1) is provided as helpful background information.

TRANSFER COEFFICIENTS TO MILK

Origin of Values in Regulatory Guide 1.109

Except for the specified values († or ‡) in Table 1, the milk transfer coefficients listed in Regulatory Guide 1.109 are from a handbook compiled by Ng et al.[13]

Estimation of Transfer Coefficients

Based on an extensive review of the worldwide literature, Ng et al.[7] systematically tabulated the milk transfer coefficients for isotopes of more than 70 elements. Milk transfer coefficients were estimated by several published approaches.[9,10] It was frequently necessary to make assumptions regarding the milk secretion rate, the kilograms of feed ingested daily by the cow, or the total activity that would be secreted in milk beyond the duration of an experiment. These considerations contribute to the uncertainty of estimates of the transfer coefficient for milk.

The F_m values tabulated here are intended to represent those expected under normal agricultural practice. In particular, values have been excluded when they are associated with diets deficient in the element under study or with diets supplemented with the stable element at levels greater than a small fraction of that in the normal or basal diet. The F_m values are reported as elemental transfer coefficients, which exceed the transfer coefficients of radioisotopes of the same element because transfer of radioisotopes to milk is accompanied by radioactive decay.[7] However, the difference between elemental and radioisotopic transfer coefficients is significant only for short-lived radionuclides.

Effect of Chemical and Physical Form

The transfer coefficient of an element to milk can vary with physical or chemical form.[7] The F_m of various chemical forms of iodine, e.g., elemental iodine, methyl iodide, sodium iodide, and sodium iodate, are comparable.[14] On the other hand, organic mercury is transferred to milk much more efficiently than inorganic mercury. The F_m of mercuric chloride is ~10^{-5} d/L(Ref. 15), and those of methylmercuric chloride[16] and phenylmercuric acetate[17] are ~40 times greater. In the case of ruthenium, which is encountered in several species and oxidation states, both the trichloride[18,19] and nitrosyl trinitrate [20] are poorly transferred to milk (F_m of $\sim 6 \times 10^{-7}$ d/L), while another unidentified chemical form is associated with an F_m of $\sim 1 \times 10^{-4}$ d/L (Ref. 21). Both polonium tetrachloride[22] and plutonium citrate[23] are transferred to milk more efficiently than their respective dioxides.[23–25] The F_m values of polonium differ by a factor of ~2.5; those of plutonium differ by a factor of >10. Both forms of plutonium are very poorly transferred to milk.

Table 2 compares transfer coefficients based on radioisotope tracer data with those based on concentrations of the naturally occurring stable isotope in milk and in the feed consumed by the animal. Careful inspection of the individual F_m estimates suggests that, for some elements, the biological availability of the chemical form that occurs in feed differs from that of the chemical forms used in the tracer experiments. The F_m values of sodium, phosphorus, potassium, calcium, zinc, strontium, molybdenum, iodine, and cesium naturally occurring in feed are comparable to those of the elements in the chemical forms used in tracer experiments. For sulfur, cobalt, selenium, and lead the F_m of the stable isotope in feed exceeds that based on the radioisotope tracer. On the other hand, the F_m based on tracer manganese in the form of $MnCl_2$ is greater than that of the manganese naturally occurring in feed.

The biological availability of radionuclides to dairy cattle may depend on their physical as well as chemical form.[7] The F_m values of ^{22}Na and $^{89,90}Sr$ in fallout from weapons tests were comparable to those of the radioisotopes used in tracer studies (Table 2). The F_m values of ^{99}Mo, ^{132}Te, ^{131}I, ^{137}Cs, and ^{140}Ba in fallout tended to be somewhat lower than those of the radioisotope tracers. The F_m of ^{54}Mn in fallout was only 2% of that for tracer ^{54}Mn in the manganous chloride form. In this case the difference in availability to the dairy cow could very well be attributed to the difference in chemical form.[7] An evaluation of the biological availability of radionuclides released from nuclear

Table 2 Effect of Chemical and Physical Forms on Transfer Coefficients to Cow's Milk*

Radionuclide	Chemical form of radioisotope	Range of individual F_m values, d/L: Radioisotope tracer data	Stable element concentrations in milk and associated feed	Radionuclides in fallout from weapons tests†
^{22}Na	NaCl	3.2×10^{-2}	4.9×10^{-3} to 6.6×10^{-2}	1.2×10^{-2} to 5.5×10^{-2}
^{32}P	Na_2HPO_4	6.9×10^{-3} to 3.4×10^{-2}	3.5×10^{-3} to 2.3×10^{-2}	
^{35}S	Na_2SO_3	7.9×10^{-3}	1.8×10^{-2} to 2.6×10^{-2}	
^{42}K	KCl	1.1×10^{-2}	4.0×10^{-3} to 1.7×10^{-2}	
^{45}Ca	$CaCl_2$, $CaCO_3$	3.3×10^{-3} to 2.3×10^{-2}	5.5×10^{-3} to 4.1×10^{-2}	
^{54}Mn	$MnCl_2$	3.0×10^{-4} to 3.5×10^{-4}‡	1.2×10^{-5} to 1.4×10^{-4}	7.0×10^{-6}
^{59}Fe	$FeCl_3$	2.0×10^{-6} to 3.9×10^{-4}‡	2.4×10^{-4} to 3.0×10^{-4}	
^{60}Co	$CoCl_2$	8.7×10^{-5} to 1.1×10^{-4}‡	2.9×10^{-4} to 1.0×10^{-2}	
^{64}Cu	$CuSO_4$	6.3×10^{-3}	6.3×10^{-4} to $\cancel{3.7} \times 10^{-3}$	
^{65}Zn	$ZnCl_2$	3.2×10^{-3} to 5.9×10^{-2}	6.0×10^{-3} to 2.6×10^{-2}	
^{75}Se	H_2SeO_3	1.2×10^{-3} to 3.7×10^{-3}	1.4×10^{-2} to 6.2×10^{-2}	
^{86}Rb	RbCl	6.6×10^{-3} to 1.9×10^{-2}	4.7×10^{-3}	
$^{85,89,90}Sr$	$SrCl_2$	3.5×10^{-4} to 3.8×10^{-3}	4.5×10^{-4} to 3.0×10^{-3}	4.5×10^{-4} to 2.7×10^{-3}
^{99}Mo	$(NH_4)_2MoO_4$	9.6×10^{-4} to 1.7×10^{-3}	7.8×10^{-4}	2.4×10^{-4} to 1.3×10^{-3}
^{132}Te	$NaTeO_3$	6.0×10^{-5} to 6.0×10^{-4}		1.1×10^{-4}
$^{125,131}I$	NaI, KI, $NaIO_3$	3.6×10^{-3} to 3.4×10^{-2}	1.7×10^{-3} to 1.8×10^{-2}	1.4×10^{-3} to 8.2×10^{-3}
$^{134,137}Cs$	CsCl	1.9×10^{-3} to 2.2×10^{-2}	3.6×10^{-3}	1.8×10^{-3} to 1.6×10^{-2}
^{140}Ba	$BaCl_2$	1.6×10^{-4} to 4.0×10^{-4}		7.0×10^{-5} to 2.7×10^{-4}
^{203}Pb	$Pb(NO_3)_2$	2.1×10^{-5} to 6.5×10^{-5}§	1.4×10^{-4} to 4.5×10^{-4}	

*Data from Ng et al.[7]

†Excludes F_m based on fallout data from Plowshare cratering events and accidental ventings of underground tests.

‡Includes data from Sam et al.[26]

§Elemental F_m for lead estimated from the F_m for ^{203}Pb.

installations to dairy cattle is not included here, but Hoffman[27] has reported F_m estimates of ^{131}I from emissions from nuclear power stations that are comparable to those of tracer ^{131}I.

Variability of Milk Transfer Coefficients

In view of the general lack of data for validating chronic-exposure models, evaluation of the uncertainties in dose predictions has relied on statistical analyses of input parameters. Hoffman[28] noted that the F_m values of strontium, iodine, and cesium were lognormally distributed and estimated the geometric standard deviation, mode, median, mean, and 99th percentile values of F_m (Table 3). The values were compared with the NRC default values of F_m in Table 1 (Ref. 4). Relative to the median (50th percentile), the Regulatory Guide F_m for strontium and iodine seem low (24th and 17th percentile, respectively). The Regulatory Guide value for cesium, 1.2×10^{-2} d/L, corresponds to the 84th percentile. Sufficient F_m data for a meaningful statistical analysis are limited to only a few elements.

Assignment of Average Transfer Coefficients

Although data for statistical studies of F_m are limited, it is still desirable to adopt a single set of generic milk transfer coefficients for radiological assessments. Table 4 lists the current recommendations of Ng et al.[7] for the average milk transfer coefficient. Generally, the F_m values in Table 4 are simply the unweighted mean of the mean values derived for an isotope from a publication. If the maxima and minima differed by more than a factor of 10, the geometric mean was estimated. On the whole, the selected values are distributed above the 50th percentile of the distribution and thus overestimate rather than underestimate the median value.

As noted above, the milk transfer coefficient can vary with the chemical form of the element. Sometimes an F_m from Table 4 is based on a specific chemical form that is listed in Ref. 10. Generally, when the F_m of two or more chemical forms of an element differ, the F_m of the form most readily transferred is listed in Ref. 10. Besides milk transfer coefficients for dairy cows, Regulatory Guide 1.109 (Refs. 3 and 4) lists milk transfer coefficients for selected elements (hydrogen, carbon, phosphorus, iron, copper, strontium, iodine, and cesium) to goat's milk.

Elemental Systematics

The regularities in the transfer coefficients of chemically related elements can readily be discerned by arranging the milk transfer coefficients of Table 4 on a periodic table of the elements[10] or by grouping the elements according to the magnitude of F_m (Refs. 7, 9, and 10). The alkali metal ions and related thallous ions and the halides and related perrhenate ions are effectively transferred from feed to milk. The lighter members of the alkaline earths and Group VI elements are also efficiently transferred from feed to milk, and the F_m values tend to decrease with increasing atomic number. The lanthanides, actinides, and ruthenium are poorly transferred to milk.

Table 3 Variability of Milk Transfer Coefficients for Dairy Cows*

Element	Geometric standard deviation	N†	F_m, d/L: Mode‡	Median‡	Mean‡	99th percentile‡	NRC‡§	Range
Strontium	1.6	19	8.9×10^{-4} (0.31)	1.1×10^{-3} (0.50)	1.3×10^{-3} (0.59)	3.5×10^{-3} (0.99)	8.0×10^{-4} (0.24)	4.5×10^{-4} to 3.8×10^{-3}
Iodine	1.7	20	7.4×10^{-3} (0.29)	1.0×10^{-2} (0.50)	1.2×10^{-2} (0.61)	3.6×10^{-2} (0.99)	6.0×10^{-3} (0.17)	2.7×10^{-3} to 3.5×10^{-2}
Cesium	1.8	27	4.8×10^{-3} (0.28)	6.7×10^{-3} (0.50)	8.0×10^{-3} (0.61)	2.6×10^{-2} (0.99)	1.2×10^{-2} (0.84)	2.5×10^{-3} to 1.6×10^{-2}

*Adapted from Hoffman.[28] The values for strontium have been reevaluated using corrected values from Ref. 7.
†Number of mean-derived transfer coefficients.
‡Values in parentheses are the percentile estimates within the distribution.
§From Table E-1 of Regulatory Guide 1.109, Rev. 1 (shows as Table 1 of this article).[4]

Table 4 Elemental Feed-to-Milk Transfer Coefficients*

Element	F_m, d/L	Approach†	Element	F_m, d/L	Approach†	Element	F_m, d/L	Approach†
H	1.4×10^{-2}	1	Mn	3.3×10^{-4}‡	1	Te	2.0×10^{-4}	1
Be	9.1×10^{-7}	1	Fe	2.7×10^{-4}	3	I	9.9×10^{-3}	2
B	1.5×10^{-3}	3	Co	2.9×10^{-3}	3	Cs	7.1×10^{-3}	2
C	1.5×10^{-2}	4	Ni	1.0×10^{-3}	3	Ba	3.5×10^{-4}	1
N	2.3×10^{-2}	2	Cu	1.7×10^{-3}	3	Ce	6.0×10^{-5}§	1
F	1.1×10^{-3}	4	Zn	1.0×10^{-2}	2	Ta	2.8×10^{-6}	1
Na	3.5×10^{-2}	2	As	6.2×10^{-5}	1	W	2.9×10^{-4}	1
Mg	3.9×10^{-3}	3	Se	4.0×10^{-3}	1	Re	1.3×10^{-3}	1
Al	2.0×10^{-4}	4	Br	2.0×10^{-2}	3	Ir	2.0×10^{-6}	1
Si	2.5×10^{-5}	4	Rb	1.2×10^{-2}	2	Au	5.3×10^{-6}	1
P	1.6×10^{-2}	3	Sr	1.4×10^{-3}	2	Hg	4.7×10^{-4}	1
S	1.6×10^{-2}	3	Zr	3.0×10^{-5}§	1	Tl	1.9×10^{-3}	1
Cl	1.7×10^{-2}	3	Mo	1.4×10^{-3}	2	Pb	2.6×10^{-4}	3
K	7.2×10^{-3}	3	Ru	3.3×10^{-6}§	2	Po	3.4×10^{-4}	1
Ca	1.1×10^{-2}	2	Ag	1.3×10^{-2}	4	Ra	4.0×10^{-4}¶	2
Ti	7.8×10^{-3}	4	Cd	1.5×10^{-3}	4	U	3.7×10^{-4}**	3
V	1.9×10^{-4}	4	Sn	1.2×10^{-3}	3	Pu	1.0×10^{-7}	1
Cr	1.1×10^{-3}	4	Sb	1.1×10^{-4}‡	1	Am	4.1×10^{-7}††	1

*Adapted from Ng et al.[7] with corrections and revisions. Sometimes an F_m is based on a specific chemical form that is listed in Ref. 10.

†The F_m values were established by the following approaches:

1. The F_m is based on the recovery of a single administered dose of a radioisotope.
2. The F_m is based on the recovery of a single administered dose of a radioisotope and on the concentrations of a radioactive or stable isotope in associated milk and feed.
3. The F_m is based on stable element concentrations in associated milk and feed.
4. The F_m values were reevaluated from the stable element concentrations in unassociated milk and feed presented in Table 4 of Ref. 7.

‡Takes into account data from Ref. 26.

§Takes into account data from Ref. 21.

¶Arithmetic mean of average values calculated by McDowell-Boyer[12] from each literature source.

**Takes into account data from Ref. 29.

††Takes into account data from Ref. 30.

TRANSFER COEFFICIENTS TO OTHER ANIMAL PRODUCTS

Origin of Values in Regulatory Guide 1.109

The F_f values in Regulatory Guide 1.109 (Table 1)[4] were estimated as the average concentration in meat divided by 50 times the average concentration in food derived from plants. The concentrations in meat and food from plants were obtained from tables in the aforementioned handbook by Ng et al.[13] Because 50 kg is the wet weight of vegetation ingested daily by cattle, F_f implicitly represents the transfer coefficient for beef.

Estimation of Transfer Coefficients

Transfer coefficients for beef and other animal products are more difficult to derive than those for milk because of the scarcity of data. The F_f to meat may be estimated by several approaches summarized in previous publications.[9,10] The F_f for eggs can be estimated by dividing the fraction of a single oral dose of a radioisotope tracer recovered in eggs by the egg production rate, measured in kilograms per day. Because meat is obtained from an animal only after slaughter, experiments in which single doses of a tracer are used to estimate the transfer coefficient to meat have been used only to evaluate the transfer coefficient to poultry, which can be studied in numbers more readily than larger species.

Transfer Coefficients from Radioisotope Data

Transfer coefficients to animal products estimated by Ng et al.[10] from radioisotope data

Table 5 Estimates of Transfer Coefficients to Animal Products from Radioisotope Data*

Element	Animal product	Number of observations	F_f, d/kg: Transfer coefficient	F_f, d/kg: Range
Sr	Beef	5	3.0×10^{-4}	6.4×10^{-5} to 5.7×10^{-4}
	Pork	3	2.9×10^{-3}	1.2×10^{-3} to 4.0×10^{-3}
	Lamb	9	1.9×10^{-3}	1.1×10^{-3} to 3.7×10^{-3}
	Chicken	8	3.2×10^{-2}	1.8×10^{-2} to 8.0×10^{-2}
	Eggs (contents)	3	0.22	0.15 to 0.26
Ru	Beef	1	2.0×10^{-3}	
	Eggs (contents)	1	4.0×10^{-3}	
Sb	Beef	1	1.2×10^{-3}	
I	Beef†	2	7.2×10^{-3}	7.2×10^{-3} to 2.0×10^{-2}
	Pork	1	2.7×10^{-2}	1.0×10^{-3} to 2.7×10^{-2}
	Chicken†	2	0.2	8.0×10^{-3} to 0.20
	Eggs (contents)	5	4.4	3.7 to 5.2
Cs	Beef	22	2.0×10^{-2}	7.2×10^{-3} to 9.3×10^{-2}
	Pork	2	0.30	0.26 to 0.38
	Lamb	7	0.12	6.1×10^{-2} to 0.25
	Chicken	2	4.4	4.3 to 4.5
	Eggs (contents)	3	0.43	0.34 to 0.53
Ce	Beef	1	7.5×10^{-4}	6×10^{-4} to 1.8×10^{-3}
Pu	Beef	2	1.0×10^{-6}	1.3×10^{-7} to 5.8×10^{-6}
	Chicken‡	1	2.0×10^{-5}	
	Eggs (contents)‡	1	3.3×10^{-5}	
Am	Chicken	1	7.2×10^{-5}	
	Eggs (contents)	1	3.9×10^{-3}	

*Adapted from Ng et al.[10]

†Based on ^{131}I data. The transfer coefficients for ^{129}I and elemental iodine were assumed to be two times the respective transfer coefficient for ^{131}I.

‡Based on plutonium as PuO_2.

are shown in Table 5. The F_f values of selected fission products and transuranic elements to beef, pork, lamb, chicken, and eggs were derived from these estimates to serve as input parameters for regional assessments of terrestrial food contamination by the routine emissions from a nuclear facility (Table 6).[8] If data were not available to derive a transfer coefficient, collateral information was used. The F_f based on collateral information and data required certain assumptions relating to similarity in the meat-to-feed concentration ratio for different species, the feed consumption rate and total body and muscle mass in different species, and similarity in the uptake and retention pattern of chemically related elements. These considerations enhance the uncertainty associated with meat transfer coefficients that are based on collateral data. In Table 6, the F_f values based on collateral information are specified (†) to distinguish them from those based on experimental data. Although the F_f values in Tables 5 and 6 have not been fully documented, they are thought to represent animals whose nutritional status is normal.

As Table 6 indicates, iodine and cesium are effectively transferred to meat and eggs. Although strontium is effectively transferred to eggs, most of it is deposited in the shell. The F_f values of strontium, ruthenium, iodine, cesium, and cerium to beef, pork, and egg contents are comparable within a factor of 3, and those of americium and curium to egg contents and milk and of plutonium to milk are comparable within a factor of 10 to those of Baker et al.[6] The F_f of cesium to chicken is identical to that of Baker et al., but for the other elements considered, the F_f values to chicken differ from those of Baker et al. by two to three

Table 6 Transfer Coefficients to Animal Products*

Element	Transfer coefficient, d/kg					
	Beef	Pork	Lamb	Chicken	Eggs (whole)	Eggs (contents)
Sr	3.0×10^{-4}	2.9×10^{-3}	1.9×10^{-3}	3.2×10^{-2}	9.0	0.22
Ru	2.0×10^{-3}	6.8×10^{-3}†	1.3×10^{-2}†	0.24†	3.9×10^{-3}	4.0×10^{-3}
I	7.2×10^{-3}	2.7×10^{-2}	6.0×10^{-2}†	0.20	3.4	4.4
Cs	2.0×10^{-2}	0.30	0.12	4.4	0.41	0.43
Ce	7.5×10^{-4}	2.5×10^{-3}†	5.0×10^{-3}†	9.0×10^{-2}†	3.0×10^{-3}†	3.1×10^{-3}†
Pu	1.0×10^{-6}	3.4×10^{-6}†	6.7×10^{-6}†	2.0×10^{-5}	2.9×10^{-5}	3.3×10^{-5}
Am	3.6×10^{-6}†	1.2×10^{-5}†	2.4×10^{-5}†	7.2×10^{-5}	3.5×10^{-3}	3.9×10^{-3}

*Adapted from Ng et al.[8]

†Transfer coefficients that were derived with collateral information and data.

orders of magnitude or more. For the transuranic elements in Table 6, the F_f values to chicken are lower by two orders of magnitude and those to beef and pork are lower by three orders of magnitude than those of Baker et al.[6] On the other hand, the F_f to beef listed for plutonium exceeds that estimated by Garten[31] (5×10^{-9} to 7×10^{-8} d/kg) by a factor of >10. Although the estimates of F_f for plutonium vary over a wide range because of the sparseness of data, the transfer of various chemical forms of plutonium from feed to animal products is very low.

Estimates of Transfer Coefficients for Beef

Estimates of F_f for beef based on stable element concentrations in meat and feed are valid only when the concentrations are obtained on meat and the feed actually consumed by the animal from whose body the meat was taken. Estimates of F_f that satisfy this requirement were reported by Little[32] for iron, copper, and molybdenum. Ng et al.[10] reported estimates of F_f to beef based on the stable element content of beef and unassociated feed. In this study the median F_f was estimated, by an extension of the NRC approach, from the median concentrations in beef and a composite feed composed of fixed proportions of grasses, legumes, and concentrates. The consumption rate by cattle was assumed to be 12 kg (dry weight) per day. The uncertainty in the estimate of F_f was evaluated in terms of σ, the standard deviation of the log-transformed F_f values, which were calculated from the σ's of the log-transformed concentrations in beef and feed assuming statistical independence. Table 7, which is a revised and corrected version of a similar table in Ref. 10, presents the median transfer coefficients together with the geometric standard deviation, the 95% interval, and the NRC value from Table 1. The limits of the 95% interval differ from the median by a factor of exp $(2.0\ \sigma)$.

Referenced estimates of the F_f to beef reported by other investigators are summarized in Table 8. The reader will note that the F_f of iron estimated from stable element concentrations in associated beef and feed, 1.2×10^{-2} d/kg (Table 8), is comparable to that estimated from stable element concentrations in beef and unassociated feed, 1.9×10^{-2} d/kg (Table 7). The F_f values of copper and molybdenum based on stable element concentrations in associated beef and forage, 9.7×10^{-4} and 1.1×10^{-3} d/kg, seem significantly lower than the respective F_f values based on stable element concentrations in beef and unassociated feed, 1.3×10^{-2} and 6.8×10^{-3} d/kg. The observed differences in the F_f values of copper and molybdenum are very likely attributable to the daily intake of molybdenum. The cattle on which F_f values of copper and molybdenum were reported in Table 8 were animals on a low-copper diet who were subjected to high dietary levels of molybdenum,[34] which leads to a lowering of the F_f for molybdenum. Furthermore, molybdenum and copper interact metabolically such that an elevation in the dietary intake of molybdenum without copper supplements leads to the depletion of copper in tissues.[35]

Transfer coefficients to beef that are largely undocumented are available in various compilations for a large number of elements (Refs. 3-6, 10, 33, and 36).

Table 7 Estimates of Transfer Coefficients to Beef from Stable Element Concentrations in Beef and Unassociated Feed*

Element	Geometric standard deviation	F_f, d/kg Median	95% interval†	NRC‡
Na	1.8	8.3×10^{-2}	2.6×10^{-2} to 2.7×10^{-1}	3.0×10^{-2}
P	1.4	5.7×10^{-2}	3.0×10^{-2} to 1.1×10^{-1}	4.6×10^{-2}
K	1.3	1.8×10^{-2}	1.0×10^{-2} to 3.0×10^{-2}	1.2×10^{-2}
Ca	1.9	7.2×10^{-4}	2.0×10^{-4} to 2.5×10^{-3}	4.0×10^{-3}
Cr	3.6	9.2×10^{-3}	7.6×10^{-4} to 1.1×10^{-1}	2.4×10^{-3}
Mn	3.1	3.9×10^{-4}	4.2×10^{-5} to 3.4×10^{-3}	8.0×10^{-4}
Fe	1.6	1.9×10^{-2}	7.5×10^{-3} to 5.1×10^{-2}	4.0×10^{-2}
Co	2.6	9.7×10^{-3}	1.5×10^{-3} to 6.3×10^{-2}	1.3×10^{-2}
Ni	2.5	2.0×10^{-3}	3.4×10^{-4} to 1.1×10^{-2}	5.3×10^{-2}
Cu	2.0	1.3×10^{-2}	3.2×10^{-3} to 4.9×10^{-2}	8.0×10^{-3}
Zn	1.6	1.2×10^{-1}	4.7×10^{-2} to 3.2×10^{-1}	3.0×10^{-2}
Rb	2.4	1.1×10^{-2}	2.0×10^{-3} to 6.2×10^{-2}	3.1×10^{-2}
Sr	3.1	5.9×10^{-4}	6.3×10^{-5} to 5.5×10^{-3}	6.0×10^{-4}
Zr	§	2.1×10^{-2}		3.4×10^{-2}
Nb	§	2.5×10^{-1}		2.8×10^{-1}
Mo	2.9	6.8×10^{-3}	8.3×10^{-4} to 5.6×10^{-2}	8.0×10^{-3}
Ag	2.5	1.9×10^{-3}	3.3×10^{-4} to 1.1×10^{-2}	1.7×10^{-2}
Ba	2.4	9.7×10^{-5}	1.7×10^{-5} to 5.6×10^{-4}	3.2×10^{-3}
W	3.8	3.7×10^{-2}	2.7×10^{-3} to 5.1×10^{-1}	1.3×10^{-3}

*Table 7 is a revised and corrected version of a similar table in Ref. 10.

†Limits of the 95% interval differ from the median by the factor exp (2.0 σ), where σ is the standard deviation of the log-transformed F_f values.

‡From Table E-1 of Regulatory Guide 1.109, Rev. 1 (shown as Table 1 in this article) or Table C-5 of Ref. 3.

§Insufficient data for statistical analysis. The estimate of F_f is associated with a large uncertainty due to the paucity of data.

Table 8 Estimates of the Transfer Coefficients to Beef

Element	Number of derived values	F_f, d/kg Mean	Range of observed values	Remarks	Ref.
Fe	3	1.2×10^{-2}	4.2×10^{-3} to 2.3×10^{-2}	From concentrations of elements in associated meat and forage	32
Cu	3	9.7×10^{-4}	2.8×10^{-4} to 1.8×10^{-3}	From concentrations of elements in associated meat and forage	32
Mo	3	1.1×10^{-3}	7.6×10^{-4} to 2.8×10^{-3}	From concentrations of elements in associated meat and forage	32
Pb	4	1×10^{-3}	2×10^{-4} to 2×10^{-3}	From concentrations of elements in associated meat and forage	12
Po		4.0×10^{-3}		Based on sheep, caribou, and reindeer data	33
Ra	15	5×10^{-4}	Undetectable to 2×10^{-3}	Based on data for cattle, caribou, and reindeer	12
Pu			5×10^{-9} to 4.1×10^{-7}		31

Table 9 Variability of Transfer Coefficient to Beef*

Element	Geometric standard deviation	N†	F_f, d/kg Mode	Median‡	Mean‡	99th percentile‡	NRC‡	Range
Cesium	2.2	24	5.8×10^{-3} (0.21)	1.1×10^{-2} (0.50)	1.5×10^{-2} (0.66)	7.3×10^{-2} (0.99)	4.0×10^{-3} (0.10)	4.7×10^{-3} to 9.7×10^{-2}

*Adapted from Little.[32]
†Number of animals studied.
‡Values in parentheses are the percentile estimates within the distribution.

Variability of Transfer Coefficients

Because of the scarcity of valid estimates of the transfer coefficients to animal products, opportunities for characterizing distributions of F_f are limited. Little[32] found that the F_f values of ^{137}Cs reported by Ward and Johnson[37] for cattle were lognormally distributed. Statistical analysis (Table 9) reveals that the NRC estimate of the F_f to beef for ^{137}Cs (4.0×10^{-3} d/kg) is approximately equal to the 10th percentile of the distribution and leads to the conclusion that the Regulatory Guide value should be revised upward. The range of F_f values exceeds an order of magnitude, and the geometric standard deviation is 2.3. In general, the variability of the F_f for beef derived from stable element concentrations in unassociated meat and vegetation is characterized by geometric standard deviations ranging from 1.3 to 3.8 (Table 7).

UPTAKE OF RADIONUCLIDES FROM SOIL BY PLANTS

Origin of Concentration Factors in Regulatory Guide 1.109

The NRC values of the soil-to-plant concentration factor B_v (Table 1) were estimated from stable element concentrations listed in the handbook compiled by Ng et al.[13] as the ratio of the average concentration in the portion of the human diet that is derived from plants and the average concentration in dry soil. These B_v values are associated with a large uncertainty because they are based on concentrations in unassociated plants and soils.

Estimation of Concentration Factors

The soil-to-plant concentration factor B_v is obtained from radioisotope experiments on plants grown in pots or other containers in laboratory greenhouses or in containers or field plots outdoors. In the absence of radioisotope data, B_v values are estimated from the concentrations of stable isotopes in plants and associated soil. The B_v values have been reported both as the ratio of the concentration in fresh vegetation to the concentration in dry soil and the ratio of the concentration in dry vegetation to the concentration in dry soil. The NRC values of B_v (Table 1) represent B_v for fresh-weight vegetation. Because the yield of forage crops and the intake of feed by livestock are typically reported on a dry-weight basis, it is convenient to report B_v values of forage crops on the basis of isotope concentrations in dry vegetation.

Variability of Concentration Factors

The uptake of an isotope from soil by plants depends on various interrelated soil properties including texture, clay content, dominant clay mineral, cation exchange capacity, exchangeable calcium, exchangeable potassium, other exchangeable cations, pH, and organic matter content.[38] It varies with chemical and physical forms of the nuclide, plant species, plant part, and stage of growth, as well as with experimental conditions such as management practice and the manner in which the isotope is introduced into the soil.

Consequently, B_v exhibits a variability that far exceeds that observed in transfer coefficients for animal products. Table 10 (Ref. 39) presents ranges of B_v values, in ratios of fresh-weight vegetation to dry-weight soil, for selected nuclides in

Table 10 Plant-to-Soil Concentration Factors for Selected Elements*

	B_v (fresh-weight vegetation/dry-weight soil)		
Element	Range of individual values†	Range of mean values‡	NRC§
Sr	1.6×10^{-3} to 6.3	7.1×10^{-3} to 2.2	1.7×10^{-2}
I	1.0×10^{-3} to 1.5	1.0×10^{-3} to 0.7	2.0×10^{-2}
Cs	2.7×10^{-5} to 0.68¶	1.3×10^{-3} to 0.17¶	1.0×10^{-2}
Pb	3×10^{-4} to 7.3×10^{-2}	5×10^{-4} to 3.5×10^{-2}	6.8×10^{-2}
Po	2×10^{-6} to 6.6×10^{-3}	2×10^{-6} to 6.6×10^{-3}	1.5×10^{-1}
Ra	7×10^{-5} to 0.75	7×10^{-5} to 0.75	3.1×10^{-4}
Th	$<9 \times 10^{-5}$ to 3×10^{-3}	$<9 \times 10^{-5}$ to 1.1×10^{-3}	4.2×10^{-3}
Pu	3.8×10^{-8} to 4×10^{-2}	5.6×10^{-7} to 9.9×10^{-3}	2.5×10^{-4}
Am	2.3×10^{-7} to 5×10^{-3}	1.1×10^{-4} to 5.0×10^{-3}	2.5×10^{-4}

*Adapted from Ref. 39.
†Estimated for a single crop–soil combination from a literature source.
‡Estimated for a crop or crop type from a literature source.
§From Table E-1 of Regulatory Guide 1.109 (Ref. 4).
¶Excludes values for sandy soils.

edible crops and forage plants. The estimation of concentration factors based on fresh vegetation usually requires assumptions pertaining to moisture content, which contributes to the uncertainty associated with B_v. The values are based on radioisotope data for crops grown in laboratory greenhouses or in the field and refer to soils of virtually every texture classification from sand to clay. Some of the B_v values are based on concentrations of naturally occurring radionuclides or stable nuclides in associated plants and soil. Except for some forage crops, the concentration factors represent the edible plant part at maturity. The B_v values are intended to reflect only the uptake of nuclides from soil via plant roots, although the effects of nuclide deposition on aboveground plant surfaces following resuspension from soil may have contributed to some of the particularly high values from field studies. Table 10 presents both the range of individual B_v values observed for a single crop–soil combination and the range of mean B_v values determined for a single crop or single crop type from a literature source. The individual values commonly vary over three or more orders of magnitude and the means over two or more. For strontium and cesium, the geometric standard deviation of the B_v for food and forage crops over all agricultural soils is estimated to be in the range of 3.5 to 4, which is ~2 times the geometric standard deviations for the milk transfer coefficients (see Table 3).

A knowledge of the dominant crops and soil characteristics of an area may be useful in reducing the range of B_v values at a particular location. The exchangeable calcium in soil is the most important factor in determining the extent of ^{90}Sr absorption by plant roots.[38,40] The B_v for strontium in various crops has been shown to be negatively correlated with the exchangeable calcium in soil.[40–42] The B_v for strontium also decreases with increasing clay and organic matter in soil.[38] Uptake of ^{137}Cs by plants from soil decreases with increasing concentrations of exchangeable potassium.[38] However, other exchangeable cations also influence cesium uptake from soil.[38,40] Elevated cesium concentration factors are associated with soils of high organic matter content, low pH, or low clay content.[42] With a knowledge of these factors, we can assume that the variability would be lower than Table 10 indicates.

Knowledge that the soils at a site are predominantly of a certain texture may be helpful in reducing the anticipated variability of B_v. Table 11 (Ref. 10) presents ranges of B_v for strontium and cesium in vegetables, grain, and forage crops grown in coarse-textured (loamy sands and sandy loams), medium-textured (loam, sandy clay loam, and clay loam), and fine-textured (silty clay and clay) soils of North America. The data suggest that if the soils in the vicinity of a site are fairly uniform in texture the concentration factors can be expected to vary over a smaller range. The loose-

Table 11 Soil-to-Plant Concentration Factors for Forage, Produce, and Grain Grown in Coarse-, Medium-, and Fine-Textured Soils*

Soil texture	Range of B_v (fresh-weight plants/dry-weight soil)	
	Strontium	Cesium
Coarse	0.011 to 1.7	4.8×10^{-4} to 0.031
Medium	2.2×10^{-3} to 0.32	4.3×10^{-5} to 2.6×10^{-3}
Fine	3.3×10^{-3} to 0.28	9.3×10^{-4} to 0.012
B_v, veg/soil†	0.017	0.01

*Adapted from Ref. 10. The data are from Refs. 41 and 43-47.

†From Table E-1 of Regulatory Guide 1.109 (Ref. 4).

textured soils are associated with the higher B_v values, the medium- and fine-textured soils with the lower B_v values. Because the coastal plain soils of the southeastern United States are predominately coarse-textured soils with an abundance of sands, loamy sands, sandy loams, and fine sandy loams, concentration factors based on coarse-textured soils were used to assess crop contamination from the routine emissions of a nuclear installation in the southeast United States [(Table 12) (Refs. 8 and 9)].

It may be possible to reduce the variability shown in Table 11 by excluding or making adjustments for B_v values derived from pot experiments in greenhouses. The B_v values for ^{90}Sr, ^{137}Cs, ^{54}Mn, and ^{60}Co measured by Steffens et al.[48] from indoor pot experiments were higher by a variable factor than those from outdoor lysimeters. However, the existence of systematic differences between B_v values from indoor pot experiments and those from field studies needs further evaluation. Sartor et al.[46] compared concentration factors for ^{85}Sr in tomato and wheat grown in large outdoor containers and in field plots. The B_v was sometimes greater for the crops grown in field plots and sometimes greater for the crops grown in containers. The results of these limited experiments suggest that large outdoor containers may simulate field conditions reasonably well.

COMPARISON WITH REGULATORY GUIDE VALUES

The data in Table 4 suggest downward revisions by a factor of 2 or more in the Regulatory Guide F_m values for iron, nickel, copper, zinc, rubidium, molybdenum, silver, tellurium, and cerium (Table 1) and upward revisions by a factor of 2 or more for cobalt and zirconium. That most revisions would be downward is not surprising because Table 3 in the handbook[13] on which most of the Regulatory Guide F_m values are based intentionally lists maximum or near-maximum transfer coefficients.

A comparison of the tracer-based F_f for beef in Table 6 with the NRC values of Table 1 supports upward revisions by a factor of 2 or more for iodine and cesium and a 200-fold downward revision for ruthenium. Table 8 presents the F_f values for beef estimated from stable element concentrations in beef and unassociated feed together with Regulatory Guide values from Table 1. Compari-

Table 12 Soil-to-Plant Concentration Factors for Regional Assessment of the Southeastern United States*

Crop	Concentration factor, pCi/kg fresh vegetation ÷ pCi/kg dry soil†						
	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs	^{144}Ce	$^{238,239}Pu$	^{241}Am
Corn	0.034	0.022	0.043†	0.026	8.6×10^{-4}	1.7×10^{-3}	1.7×10^{-3}
Wheat	0.27	8.9×10^{-3}	0.045†	0.045	1.3×10^{-3}	1.8×10^{-3}	1.8×10^{-3}
Barley	0.27	8.9×10^{-3}†	0.045†	0.045†	1.8×10^{-3}†	1.8×10^{-3}	1.8×10^{-3}
Tomatoes	0.024	6.0×10^{-4}	0.018	7.2×10^{-3}	2.4×10^{-5}	9.0×10^{-5}†	2.4×10^{-4}†
Cabbage	0.08†	8.0×10^{-3}†	0.024	4.0×10^{-3}†	3.2×10^{-3}†	1.2×10^{-4}†	3.2×10^{-3}†
Sweet corn	0.011	6.8×10^{-3}	0.014†	8.1×10^{-3}	2.7×10^{-4}	5.4×10^{-4}†	5.4×10^{-4}
Snap beans	0.03	1.5×10^{-3}	0.04	5.0×10^{-3}	1.0×10^{-4}	1.5×10^{-4}†	1.0×10^{-4}†
Irish potatoes	0.06	6.0×10^{-4}	0.024	0.02	3.0×10^{-4}	1.2×10^{-3}	1.2×10^{-3}
Hay	0.72	0.090	0.18	0.14	9.0×10^{-3}	9.0×10^{-4}	1.8×10^{-3}
B_v, veg/soil‡	0.017	0.05	0.02	0.01	2.5×10^{-3}	2.5×10^{-4}	2.5×10^{-4}

*Adapted from Refs. 8 and 9.

†Estimated from collateral information and data.

‡From Table E-1 of Regulatory Guide 1.109 (Ref. 4).

[illegible] of the NRC estimate of F_f with the 95% interval indicate that the NRC estimates for beef are calcium, nickel, silver, and barium may be too high and the estimates for zinc and tungsten may be too low as representative midrange values.

The large variability associated with soil-to-plant concentration factors severely limits the usefulness of a single B_v to predict the concentration of a nuclide in crops from that in soil. A cursory comparison of the NRC values of B_v for strontium and cesium and the B_v values in Tables 11 and 12 leads to the conclusion that the Regulatory Guide estimate for strontium (0.017) should be raised. This value is below the concentration factor of virtually all the crops studied in coarse-textured soils (see Table 12) and is below those of many crops in medium- and fine-textured soils. The B_v of 0.2 suggested by Baker et al.[6] seems more appropriate as an approximately midrange default value for strontium if one recognizes that its use would still underestimate the concentration of strontium in some crops and soils. The Regulatory Guide estimate for cesium (0.01) does not seem unreasonable. It is below the concentration factor for forage, potato, and grains in coarse-textured soils (see Table 12), but it exceeds that observed for crops in medium- and fine-textured soils except forage. In coarse-textured soils the Regulatory Guide estimate for ruthenium (0.05) exceeds the B_v in all the food crops examined, and that for cerium (0.0025) exceeds the B_v in most of the food crops examined. The Regulatory Guide estimate of the B_v for lead and thorium are comparable to the maxima listed in Table 10 and that for polonium exceeds the maxima.

A promising approach to reduce the uncertainty associated with plant-to-soil concentration factors is to adopt average values of B_v for each main crop type, e.g., leafy vegetables, other aboveground vegetables, root vegetables, grain, and forage.[36,39] The variability and uncertainty in the concentration factor can potentially be reduced further from a knowledge of the properties of the specific soil types that predominate at a site or region.

SUMMARY AND CONCLUSIONS

Updated transfer factors have been derived to predict concentrations of radionuclides in terrestrial foods using currently available equilibrium models. Experimentally based transfer coefficients to cow's milk (F_m), transfer coefficients to beef and other animal products (F_f), and soil-to-plant concentration factors (B_v) for a large number of nuclides are presented and compared with those in Table E-1 of Regulatory Guide 1.109 (Ref. 4) and similar tables. These comparisons lead to suggested changes, both increases and decreases, in the current estimates.

The B_v values are shown to be extremely variable depending on crop type and various soil properties and environmental factors. Predictions of radionuclide concentrations in crops based on a single generic estimate of B_v must therefore be interpreted cautiously with due consideration of a wide range of concentration factors. The uncertainties associated with predictions of radionuclide uptake by plants from soil at a particular location may be reduced by considering the principal crops and soil types of the region and how various soil properties influence B_v.

The updated transfer factors may be useful as generic input parameters for radiological assessments when site-specific information is not available. Together with judicious application of collateral information, they provide a basis for a systematic revision of Table E-1 of Regulatory Guide 1.109 (Ref. 4) and similar compilations of transfer factors for assessing the dose from radionuclides in agricultural products.

The estimation of transfer coefficients for beef and other nondairy animal products and of soil-to-plant concentration factors for food and feed crops grown in agricultural soils are topics that need integration and more complete documentation. It is hoped that efforts will soon be forthcoming to correct these deficiencies.

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